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RESIDENTIAL MAGNETIC FIELDS - ACCOUNTING FOR EXTERNAL SOURCES AND RESIDENTIAL GROUNDING CIRCUITS

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A project to characterize the sources of magnetic fields in residential locations has been established as part of Ontario Hydro's program to assess the risks, if any, posed by fields due to the electric power system. In this report a simple model for the strength of the magnetic field at 60 Hz found inside houses is developed to account for the house wiring, and for sources external to the house. In the model the house wiring is reduced to a single circuit carrying the net current on the service drop to the house and the service grounding current. All sources external to the house are combined and represented as a single ambient field assumed to be spatially uniform throughout the volume of the house. This model and a measurement procedure were tested on five houses in locations inside the houses remote from appliances, which were not included in the model. In the main, good agreement was found between actual measured field strengths and those predicted by the model.

1. Introduction

A concern of the health effects of low frequency magnetic fields has been raised by epidemiologic studies of childhood cancer in relation to proximity to electric power distribution lines. To address this concern, Ontario Hydro has set-up the Electric and Magnetic Field Risk Assessment Program which consists of laboratory studies of rodents, development of instrumentation to measure the fields in industrial and residential environments, and a characterization of the sources of the fields in these environments. The epidemiologic study by Savitz et al/1/ found elevated incidences of cancer in residential locations that are close to high-density wiring

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configurations, but did not find a similar relation in terms of magnetic field exposure. This result lead Savitz et al to the conclusion that further investigation is required to improve exposure assessment.

This report describes the development and testing of a simple model for computational dosimetry, in which the exposure of a child is calculated from a small number of measured quantities.

The purpose of this study was to:

1. Develop a simple model for computational dosimetry for children in their homes.

2. Gain experience in the validity of the model by testing it in several houses.

3. Establish a measurement procedure for future studies.

The study was limited to magnetic fields and did not include electric fields. The location considered was the interior volume of the houses and did not include streets, schools or other locations. The sources of magnetic fields included were all sources exterior to the house, and house wiring. Appliances were not included in the model or measured in the houses.

2. Experimental Procedure

The initial study involved a group of four scientists, but for future studies optimization of this procedure is necessary so it can be performed by a single scientist/epidemiologist.

The procedure went as follows: The team of scientists arrived at the specific location equipped with field and current measuring devices, plans of the electrical distribution network and water-pipe network for the neighbourhood and a tape measure. The following steps outline the initial source-characterization procedure.

1. The conductors inside the house were traced physically by observation and also with an Ontario Hydro built three-axis sniffer/2/.

2. A Cartesian coordinate system was established for the house and the conductors in the house were surveyed.

3. A pair of Hydro linemen were on site to measure the current on the distribution network directly in front of the house. The current on the lines on neighbouring streets was measured if the the network formed a small current loop around the house. The magnetic field is inversely proportional to the distance from the current source and consequently, a small current loop may result in a substantial field (due to the distribution network) in the house.

4. The magnetic field was measured in the grounds of the house and on the street in front of the house, where the water main is located.

5. A Data Acquisition System was used to monitor the current on the grounding circuit, and the total field in the house. An auxiliary coil was placed in a remote corner of the house to monitor the ambient field present due to external sources. The Data Acquisition System was left monitoring overnight.

3. Result and Discussion

3.1 The Measurements

23 Brunner Avenue, Etobicoke: Part of the distribution network that feeds 23 Brunner is shown in Fig 1. There are three separate sections of 2.4 kV primary line (denoted by L in the figure) making up a possible current loop around the house. The transformers are also marked in the figure and they step-down the voltage to the 240 V secondary bus (denoted by H). A system neutral is connected all around the circle and is omitted in the figure. Etobicoke Hydro linemen measured the current on the primary and and secondary bus connected to the transformer in front of 23 Brunner and on the primary and secondary bus on Decarie Circle at the Brunner junction (see Fig 1). The currents measured were as follows:

1. A 10 Amp current was measured on the primary to the east of 23 Brunner that connects to the transformer in front of the house.

2. A net current of 1 Amp was measured on the secondary bus to the east of the transformer.

3. A net current of 5 Amps was measured on the secondary bus to the west of the transformer.

4. A current of 16 Amps was measured on the primary on Decarie Circle and a net current of 5 Amps was observed on the secondary bus.

These results indicate that a net current was flowing on the Hydro network that circles the house. A theoretical value of the ambient field can be calculated from the net current in the network (Section 3.2) which can be compared to the measured value. Quantitative agreement of better than 10 % was obtained between the two values.

A magnetic field was observed in the back yard of the house using a Leeper meter (a hand held, battery operated device that uses a pick-up coil to measure the magnetic field) with the main switch open and closed. With the circuit open (ie no power to the house), approximately 1 mG (vertical) field was measured in the front and back yard and the field increased as the Hydro lines were approached. With the house circuit closed (power to the house), the 1 mG (vertical) field was still present in the back yard, but in the front yard the field had increased to approximately 2.5 mG (45 degree orientation) and the field increases to 3 mG (horizontal) directly under the service drop. The magnetic field resulting from the current flowing on the cast-iron water main was substantially less than 1 mG.

The service drop to 23 Brunner consists of 3 conductors, a 120 V line, a -120 V line and a system neutral. These conductors are wired into the residential fuse box and the system is grounded through a copper wire, clamped to the water-pipe. This is illustrated in Fig 2.

The Data Acquisition System was placed by the water-pipe (where the grounding connection was made) to monitor the magnitude and phase of the water-pipe current, the magnitude and phase of the total magnetic field at this location. A coil located in a remote part of the basement monitored the magnitude and phase of the ambient field produced by sources external to the house. The Data Acquisition System was operated for approximately 8 hours and over that period it accumulated eight frames of results, each frame consisting of 128 sampled events. Each event consisted of two cycles of ac power. The Data Acquisition System monitored the real time evolution of the 60 Hz waveform over that duration and then stored the rms (root mean squared) value for that event/3/.

The ambient field measured by the Data Acquisition System agreed with the ambient field measured in the back yard of the house using the Leeper meter.

Figure 1. 23 Brunner Ave. distribution network.

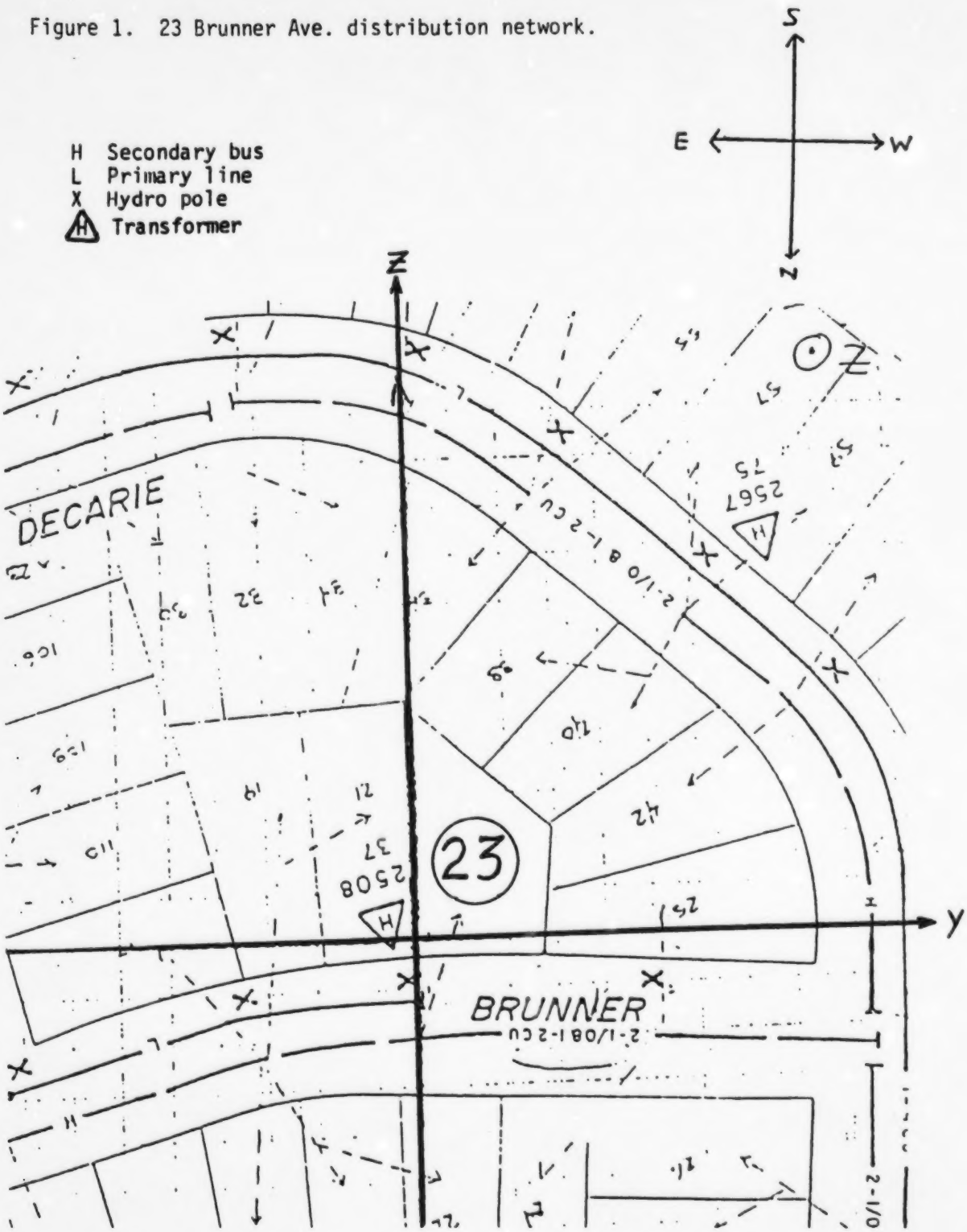

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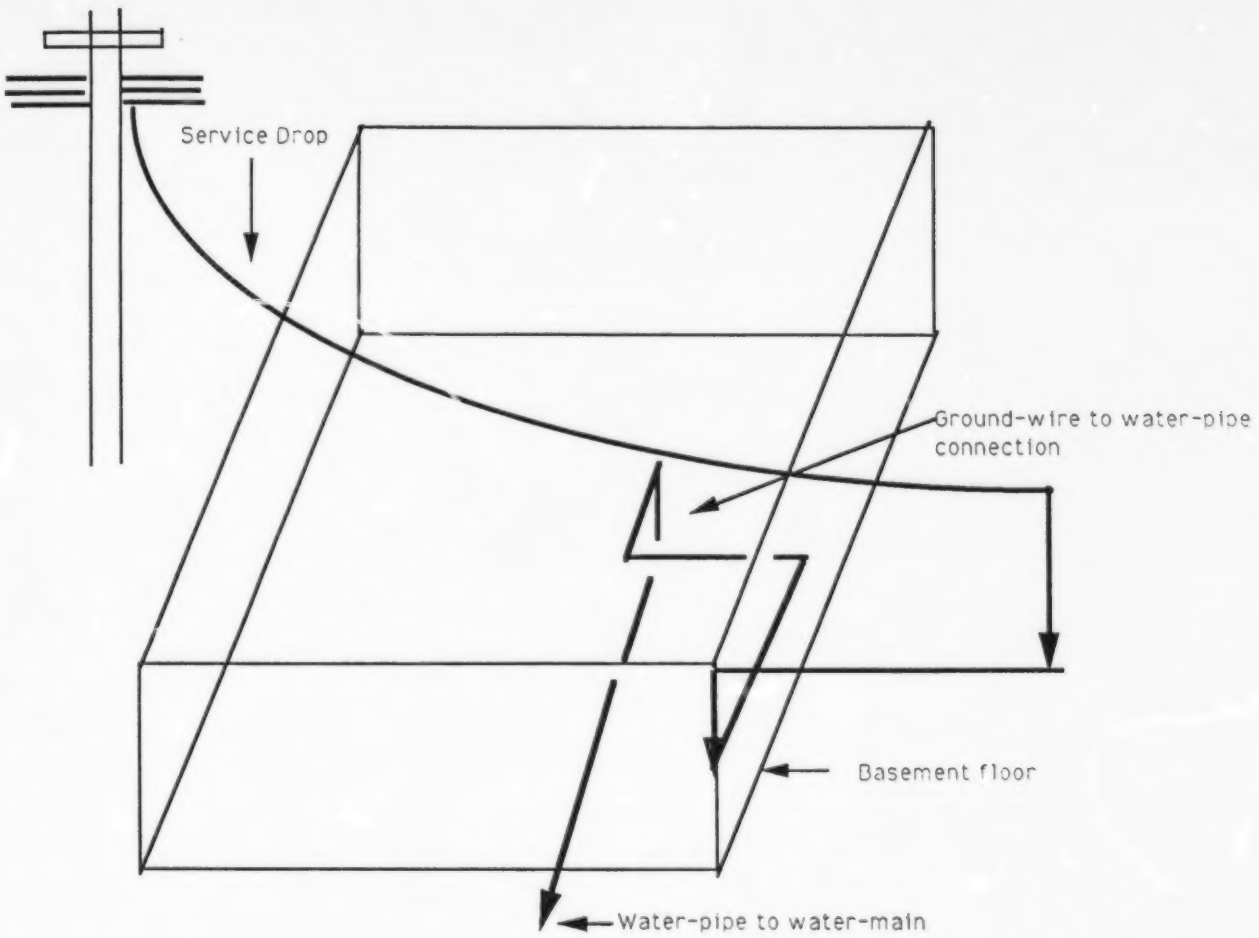
Figure 2. 23 Brunner Ave : House Network



5 Palace Arch Drive, Etobicoke: The distribution network supplying this location is given in Fig 3. The figure indicates the location of the primary and secondary bus and the transformers along Palace Arch Drive. Any potential current loop the electrical distribution network makes around the house covers too large a distance to be of importance. As mentioned in Section 2, the magnetic field is inversely proportional to the distance from the source and consequently the field in a house surrounded by a loop of large area would be small. The Etobicoke Hydro linemen could not measure the net current on the secondary bus (due to deteriorated insulation problems) so the currents on the three secondary lines (240 V) were measured separately as well as the current on the primary line (2.4 kV). Measurements were made on the bus on both sides of the transformer which is located adjacent to the south side of the house.

1. A current of 18 A was measured on the primary on both sides of the transformer.

2. The currents measured on the secondary bus were 36 A (120 V line), 10 A (neutral) and 58 A (-120 V line) on the south side of the transformer and 80, 12, 88 A respectively on the north side of the transformer.

3. A net current of 4 A was measured on the service drop which corresponded to a net current of 3.25 A on the water-pipe measured at that time.

It is difficult to determine the net current on the secondary bus as we do not know the phase of the current flowing in the individual conductors.

An ambient field of less than 0.5 mG was observed in the back yard with the power switch at the service panel turned off (ie the electrical power to the house is off). Substantially higher fields were produced by the TV cable and Bell telephone lines located in the back yard, but these had little effect on the field measured in the house. High magnetic fields were observed in front of the house above the water-pipe and under the service drop.

The Data Acquisition System was placed in the laundry room to monitor the current on the grounding circuit, the total magnetic field in the house and the ambient field in the house due to external sources. The coil used to measure the ambient field was placed in a remote corner of the house so as not to pick up the magnetic field due to the grounding circuit. The grounding network is illustrated in Fig 4.

Figure 3. 5 Palace Arch Dr. : Distribution Network

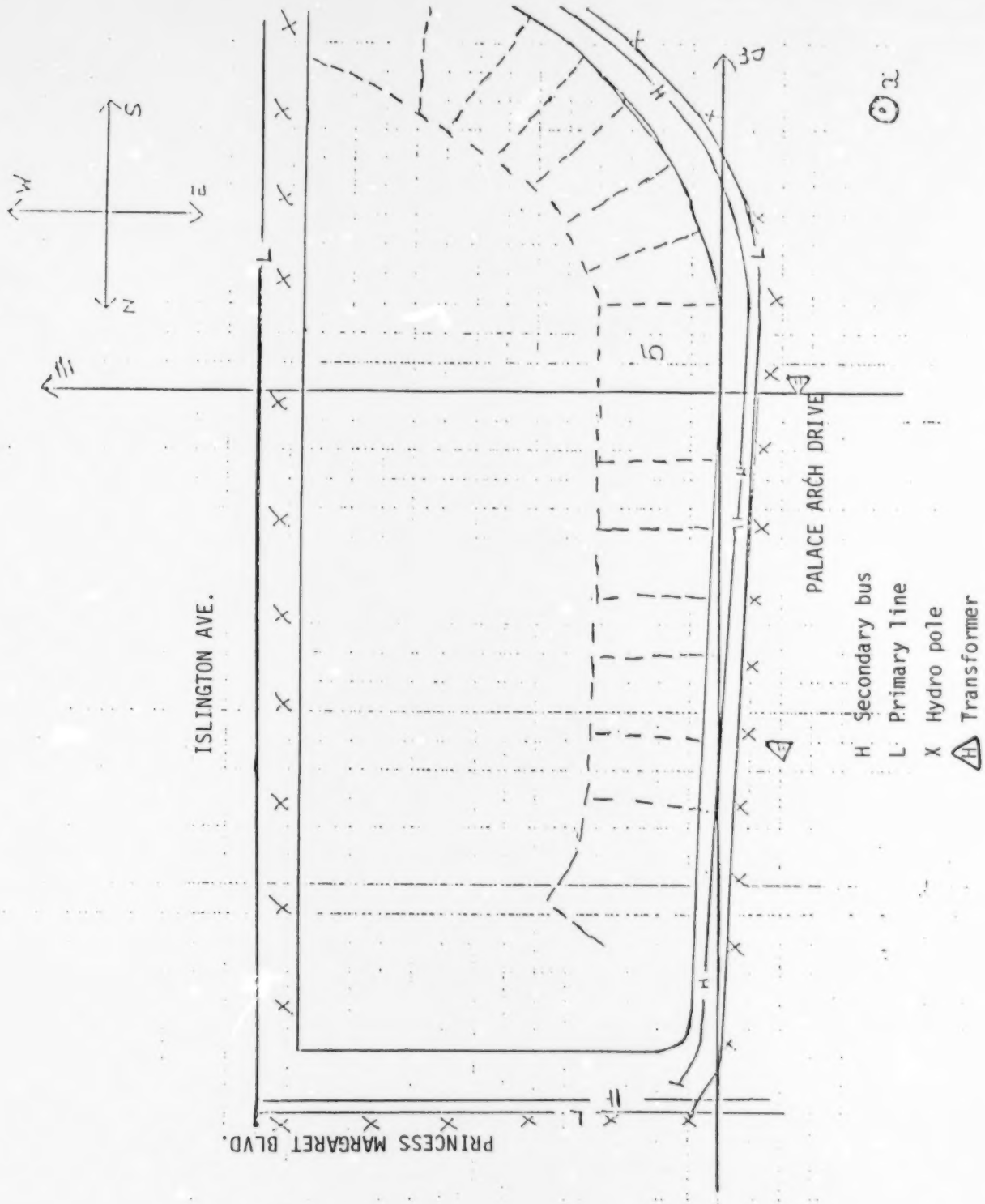


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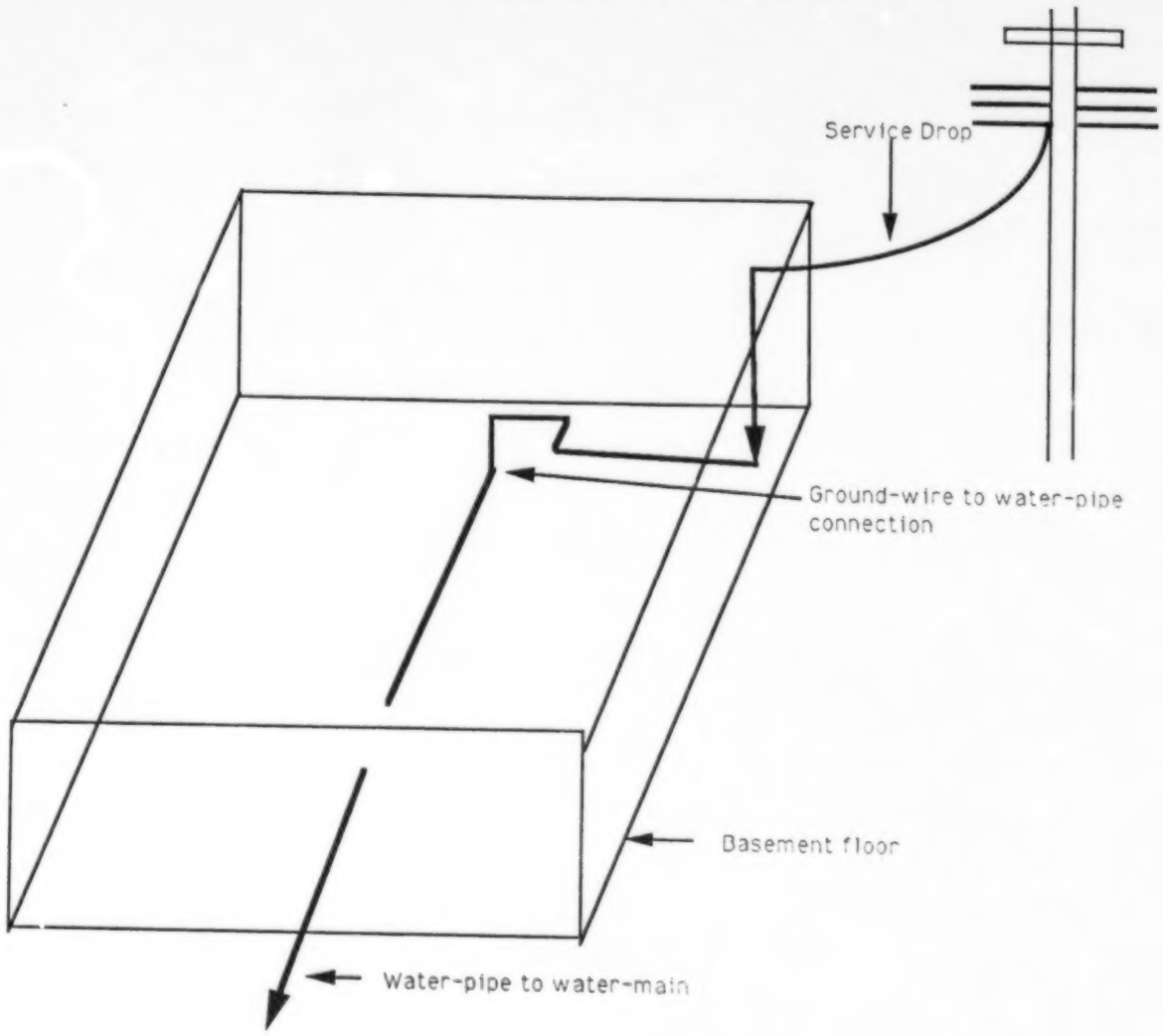
Figure 4. 5 Palace Arch Dr. : House Network



85 Rayne Avenue, Oakville: The Hydro distribution network for this location is shown in Fig 5. The network is located at the back of 85 Rayne and the secondary that feeds the house is connected to the transformer to the east of the house. The Oakville Hydro linemen measured the current on the primary (8 kV) which spans the whole street and on the two secondary buses (240 V) which are connected to the pole at the back of 85 Rayne. These secondary buses are connected to different transformers, one to the east of the house and the other to the west of the house.

1. A current of 4 A was measured on the primary.

2. A net current of 6 A was measured on the secondary bus directly behind the house and a net current of 4 A was measured on the secondary bus west of the house.

3. A net current of 3 A was observed on the service drop.

Very little ambient field was picked up in the front or back of the house, typically less than 0.5 mG. However, larger fields were observed in specific locations in the front yard indicating the presence of the water-pipe.

The house grounding network for this house turned out to be quite complex due to an inadvertent ground connection made by the heating duct touching the water-pipe. This configuration is illustrated in Fig 6. A 240 volt supply (with a ground) is wired from the service box to an air conditioning unit located on the outside of the house. The Freon line of this air conditioning unit makes a connection to the hot air heating duct which is physically pressed against the water-pipe at location (+) in the figure. This establishes another return current path as the current can travel through this circuit and out through the water-pipe. The clamp connecting the installed grouding wire to the water-pipe was loose, causing the inadvertent path to carry most of the ground current. The Data Acquisition System was positioned at the ground wire/water-pipe location to monitor the current on the grounding circuit, the total magnetic field in the house and the ambient field due to external sources. The ambient field coil was put in a remote corner of the basement so as not to pick up any magnetic field due to the grounding circuit.

7 Storey Crescent, Etobicoke: Figure 7 gives a layout of the distribution network for 7 Storey Cr. and neighbouring streets. Directly in front of the location there is a 240 volt secondary bus and the corresponding primary is located further down the street. There is also no primary line on the part of Dewitt Rd. that forms part of a semicircle around 7 Storey Cr. The third street of this loop is Massingham Rd. and the primary line extends approximately 2 houses into the road where it is transformed to a 240 V secondary line. Etobicoke Hydro linemen were on hand to make current measurements on all three streets. However, because the insulation on the wires was deteriorated they were unable to bunch the wires of the secondary bus together to obtain a net current reading directly. All that could be obtained were current readings of unknown relative phase on the individual wires. Thus the net current could not be obtained.

Figure 5. 85 Rayne Ave. : Distribution Network

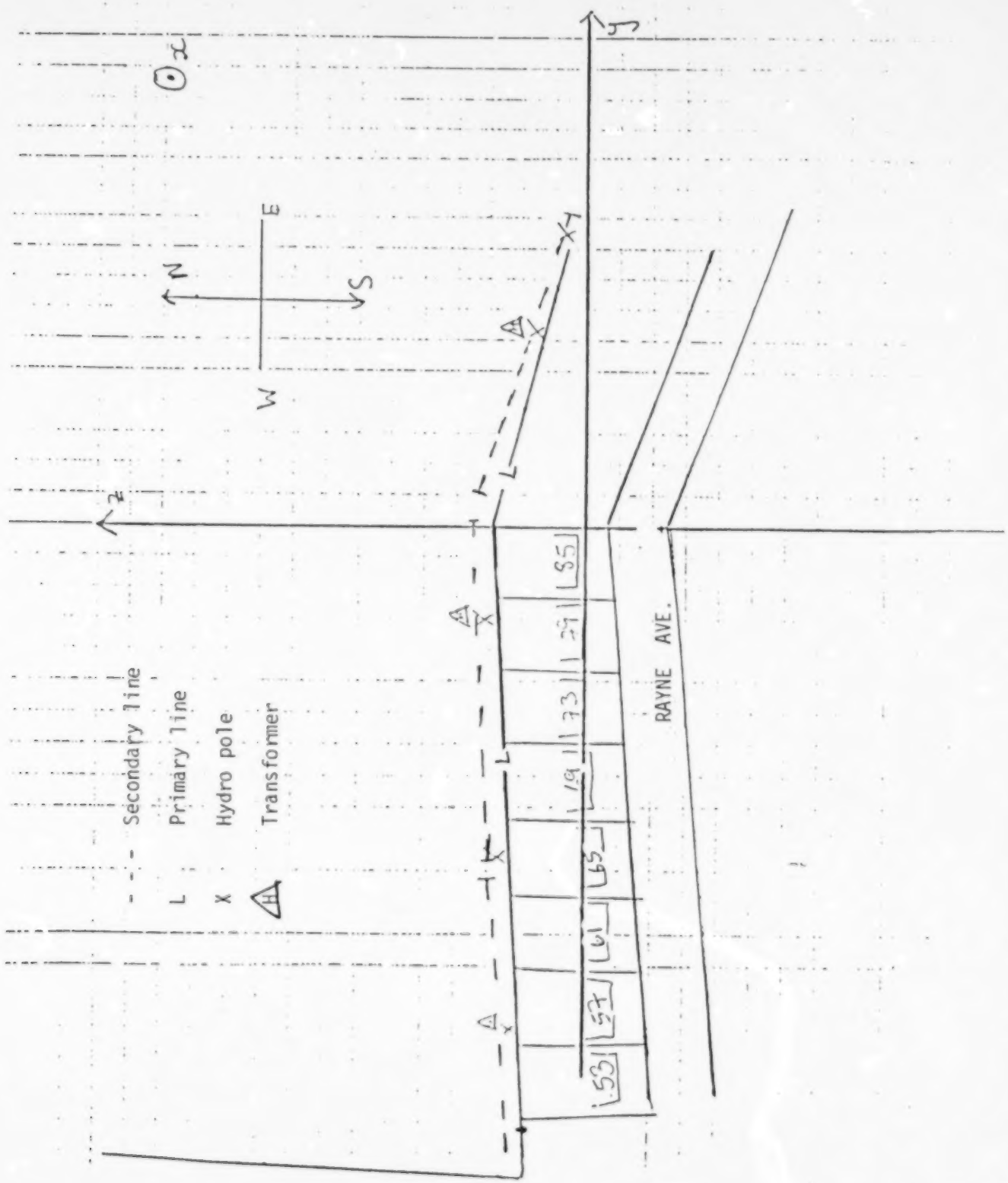


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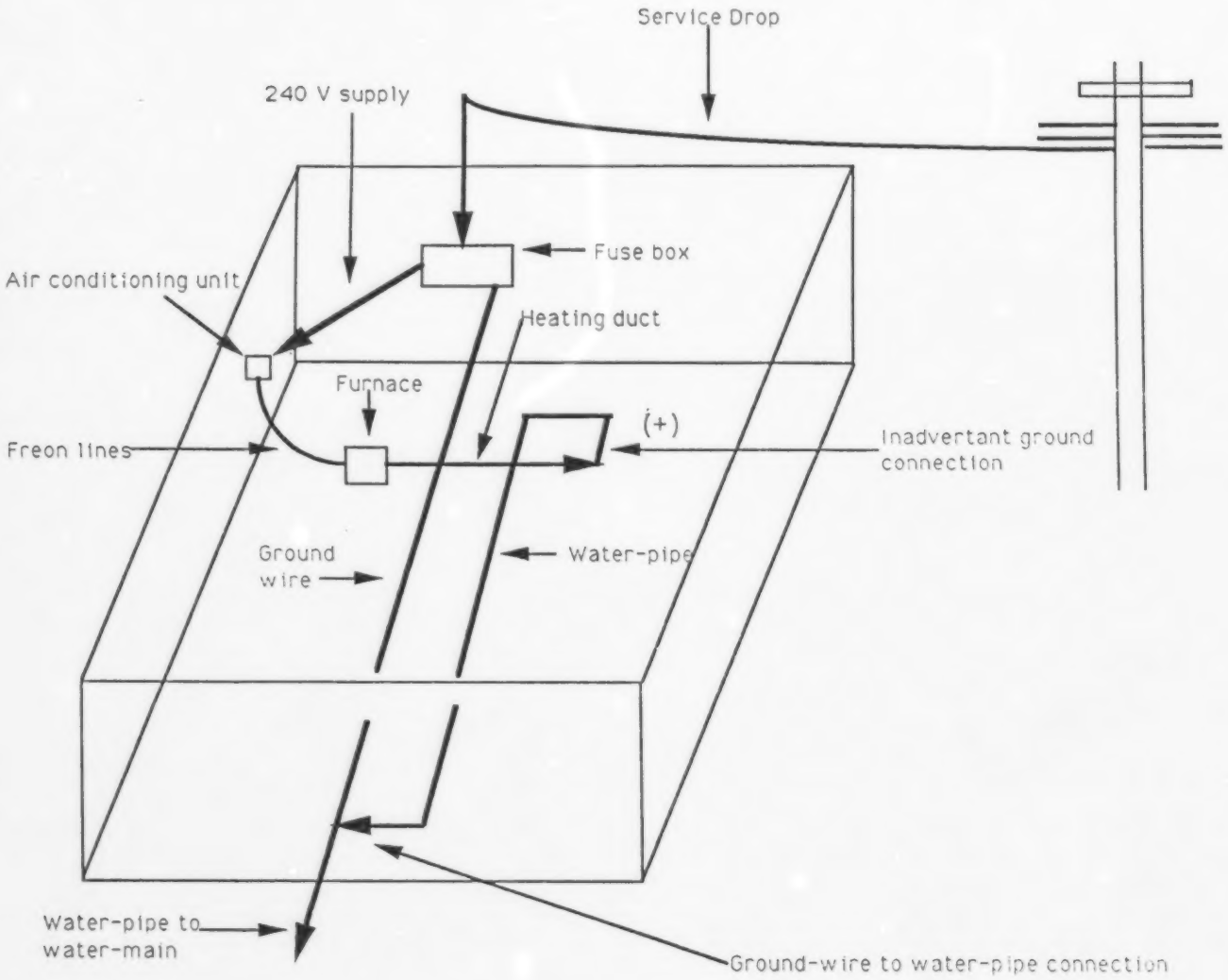
Figure 6. 85 Rayne Ave. : House Network



1. The current on the secondary bus outside 7 Storey Cr. was 10 A (120 V), 7 A (neutral), and 3 A (-120 V).

2. The current on the secondary bus on Dewitt Rd. was 9, 5 and 15 A, respectively.

3. The current on the primary on Massingham Rd. was 15 A and the current on the secondary was 30, 5 and 60 A, respectively.

Again the problem with not measuring the net current on the secondary bus is that we do not know the phase of the currents to be able to estimate net current.

The house grounding network consisted of a ground connection from the service panel to the water-pipe permitting two possible return paths for the current, see Fig 8.

69 Gates Crescent, Ajax: The distribution network for this location is an underground network and so no current measurements were taken. However, this house can still be used in the study, because the these current measurements are made to try and obtain a quantitative agreement between the ambient field measured in the house and the current on the distribution network (refer to Section 3.2). For this location, the ambient field measured was less than 0.05 μT and a comparison with the current on the distribution network would not be worthwhile.

The magnetic field measured over the underground distribution network in front of the house was large. Independent authors/4/ have also identified the fields observed over an underground distribution system as being higher than those under an overhead network. This can be attributed to the closer proximity of the underground cables.

The configuration of the house grounding network is given in Fig 9. The Data Acquisition System was placed at the location were the ground connection is made to the water-pipe and the auxiliary coil was placed in a remote corner of the basement to monitor the ambient field.

Figure 7. 7 Storey Cres. : Distribution Network

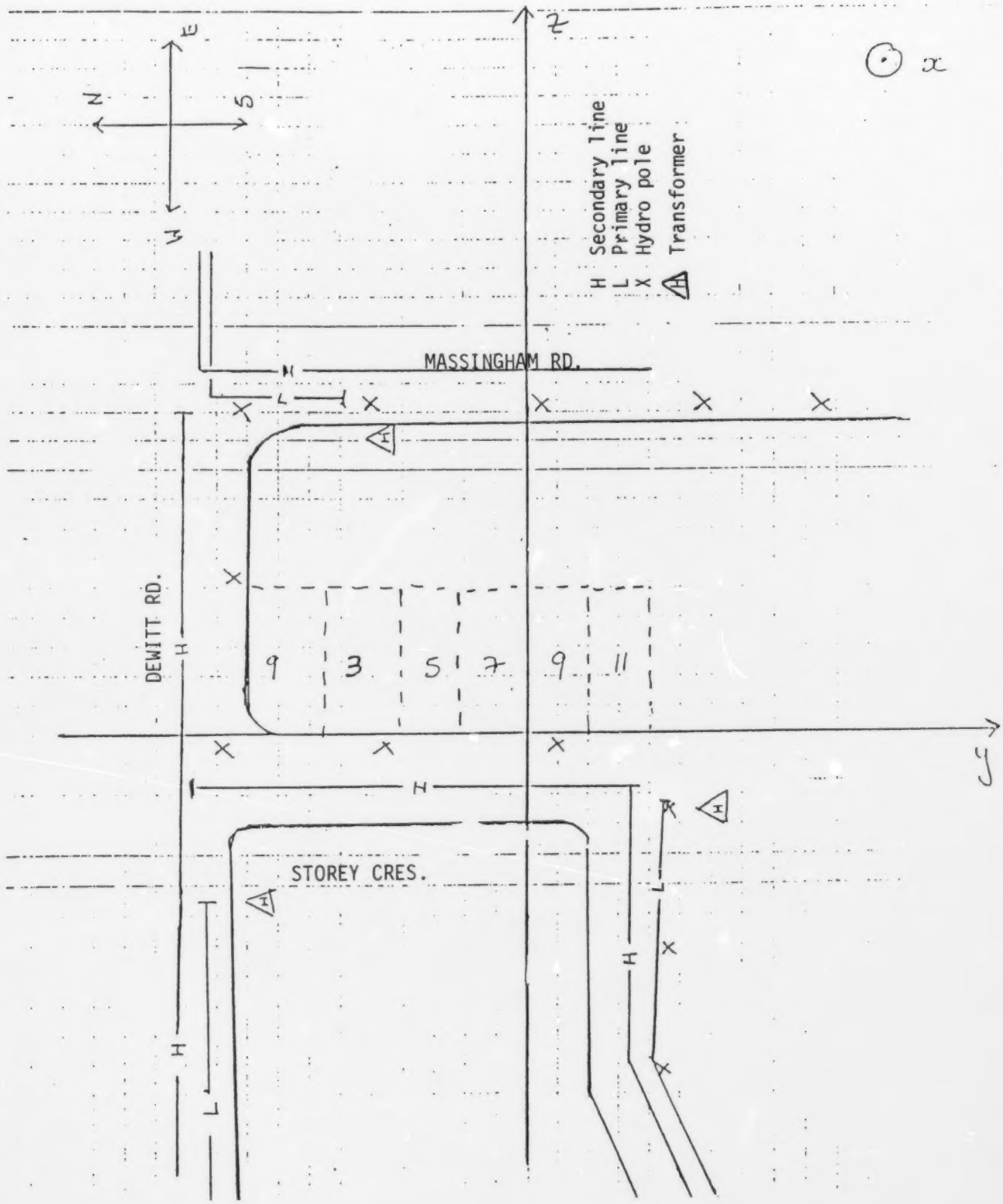


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Figure 8. 7 Storey Cres. : House Network

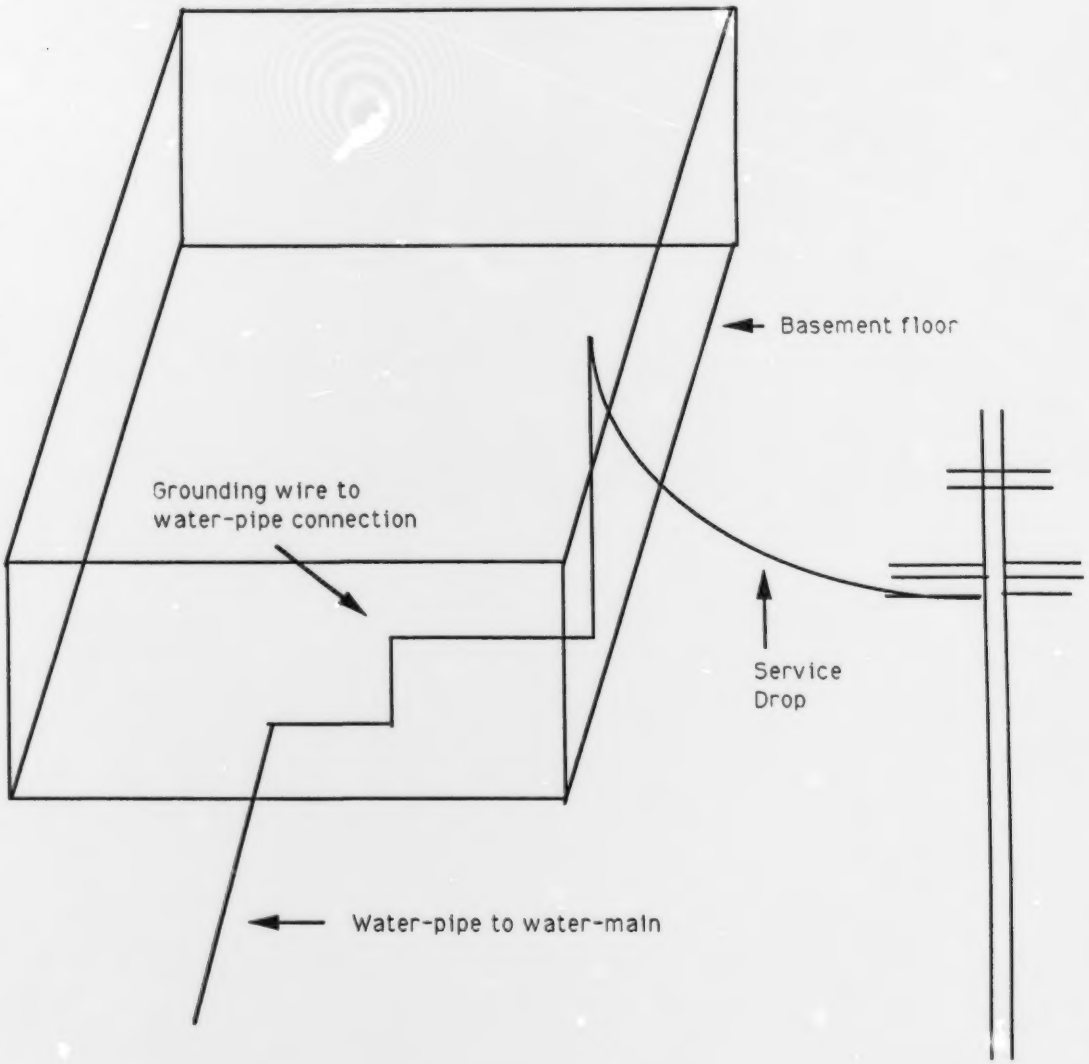
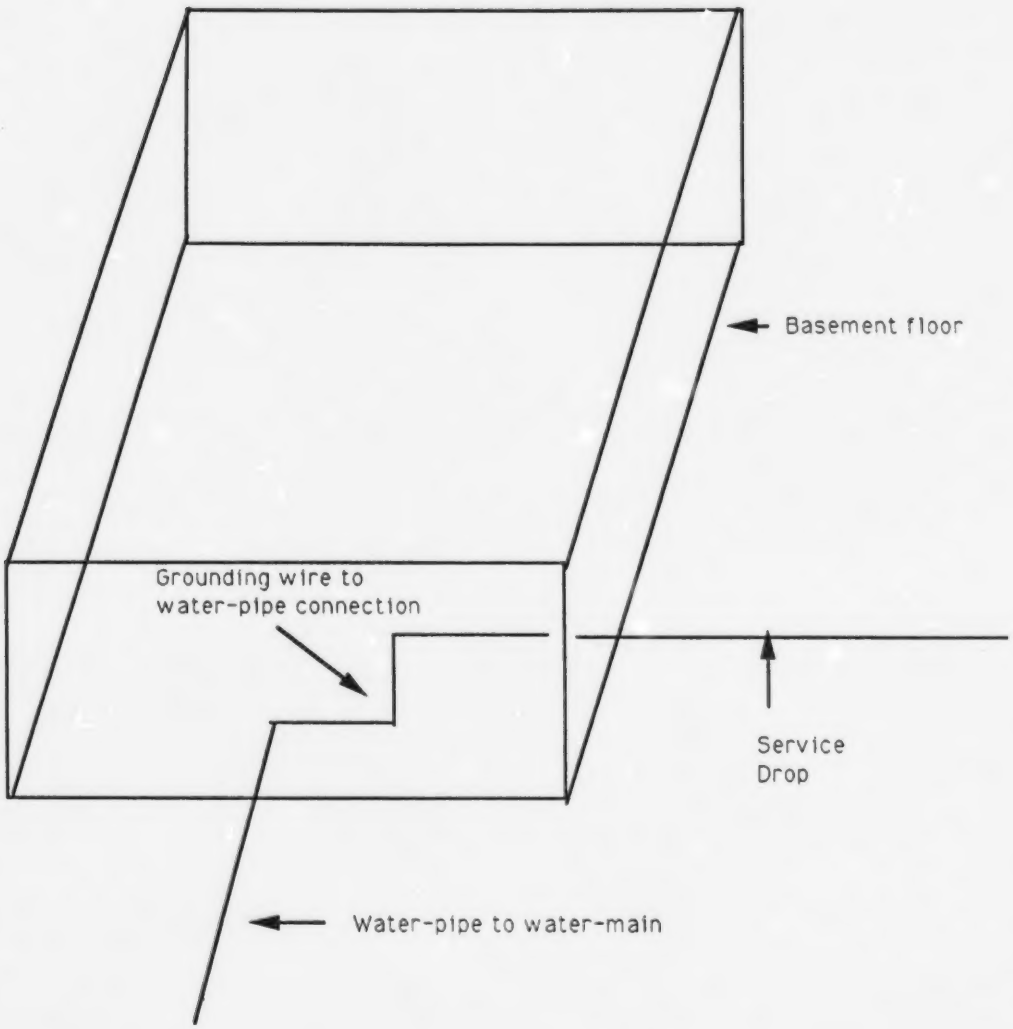


Figure 9. 69 Gates Cres. : House Network



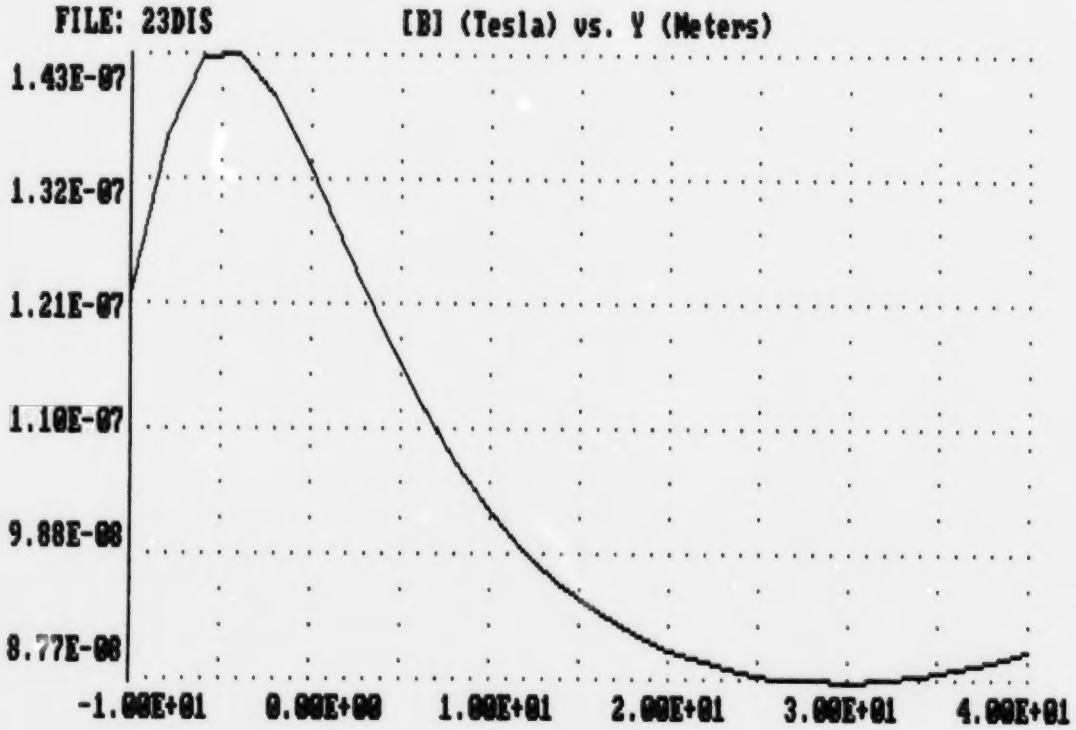
3.2 Theoretical prediction of the ambient field at 23 Brunner Avenue.

A coordinate system was established to identify the various locations of importance, ie the house grounding network, the distribution network etc. The positions of the Hydro poles forming a loop around 23 Brunner Avenue, Fig 1, were entered into a program called MAG-PC which uses the Biot-Savart law to calculate the magnetic field for a given current at a specified location. The current loop around 23 Brunner is assumed to be a single conductor split into four sections, each section having a different net current. This is illustrated in Fig 1, where, for example, the primary line and secondary bus along Decarie Circle are assumed to be one conductor with a net current of 9 A, ie the net current of 4 A on the secondary bus is assumed to be out of phase with the current of 16 A on the primary.

Figure 10 is a typical MAG-PC output and shows the calculated total magnetic field as a function of distance for a line along the side of 23 Brunner; from the Hydro pole to the back yard. It is apparent from the figure that at the back of the house the field is spatially uniform and has a magnitude of approximately 0.1 μT. A spatially uniform field of magnitude 0.1 μT was also observed experimentally in the back yard. Consequently, the ambient field at this location has been modelled in terms of a single conductor loop with a net current. Agreement of better than 10 percent is achieved with the experimental values.

The ambient field (ie external sources) can, therefore, be modelled as a spatially uniform field and this assumption will hold for locations where the external sources are not in close proximity to the house.

Figure 10. A typical output from MAGPC



3.3 The Formula

The positions of the grounding network in relation to the same Cartesian coordinate system used in Section 3.2, were entered into MAG-PC along with the current on the network. MAG-PC creates an output data file containing the x,y and z components of the magnetic field as well as the total field, for selected coordinates.

We now have the basis to formulate a theoretical description of the sources of magnetic field at a particular location. If the magnetic field varies sinusoidally with time then the general form can be written as:

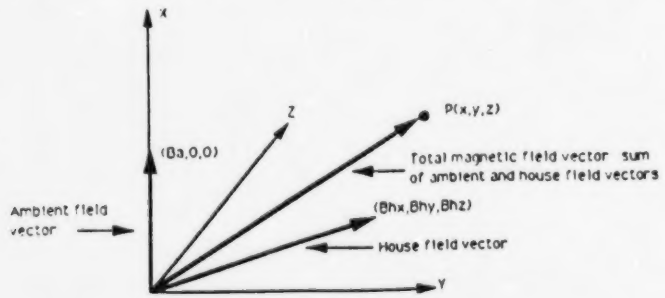
$$B_i(P,t) = A_i(P)\cos(wt + \delta). \qquad (1)$$

Here A is the amplitude, w is $2\pi f$, where f is the frequency, δ is the phase of the field. and i=x,y or z.

The magnetic field in the house can be written in terms of two components, the field due to the house conductors (the grounding network) and the ambient field (field due to the distribution network), ie

$$B_i(P,t) = B_{hi}(P,t) + B_{ai}(P,t), \qquad (2)$$

where P is the coordinates of an arbitrary position in space and t is the time.



The field components can be written as:

$$B_{hi} = B_{hi}\cos(wt + \delta_h). \qquad (3a)$$

$$B_{ai} = B_{ai}\cos(wt + \delta_a). \qquad (3b)$$

and using common trigonometric identities, the total field is then given as:

$$B_i = (B_{ai}\cos\delta_a + B_{hi}\cos\delta_h)\cos wt + (B_{ai}\sin\delta_a + B_{hi}\sin\delta_h)\sin wt$$

$$= f_i\cos wt + g_i\sin wt = A_i\cos(wt + \delta). \qquad (4)$$

where f and g are the quadrature components of the field B. Therefore, we can write the amplitude and phase in terms of f and g, ie

$$A^2_i = f^2_i + g^2_i \qquad \text{and} \qquad \delta = \tan^{-1} g_i/f_i$$

where,

$$f_i = B_{ai}\cos\delta_a + B_{hi}\cos\delta_h \tag{6a}$$

$$g_i = -(B_{ai}\sin\delta_a + B_{hi}\sin\delta_h) \tag{6b}$$

It proves convenient to write the magnetic field due to the grounding circuit in a house in terms of a unit magnetic field (U(P)), which is the magnetic field corresponding to 1 A of current for a specific configuration.

$$B_{hi}(P) = U_{hi}(P)\, I_h. \tag{7}$$

Assuming the ambient field is spatially uniform and only has an x component, then this field has the form, $B_a = (B_{ax},0,0)$.

The house current used in the equation (7) and the ambient field used in equations (6) can be obtained from the Data Acquisition System, which measures rms (root-mean-squared) values, $I_{hrms}(t)$ and B_{arms}. Then equations (6) and (7) can be written as:

$$B_{hirms}(P) = U_{hi}(P)\, I_{hrms}. \tag{8a}$$

$$f_{irms} = B_{airms}\cos\delta_a + U(P)_i I_{hrms}\cos\delta_h \tag{8b}$$

$$g_{irms} = -(B_{airms}\sin\delta_a + U(P)_i I_{hrms}\sin\delta_h) \tag{8c}$$

The total rms magnetic field squared is the sum of the squares of the rms components, ie

$$B_{rms}^2(P) = B_{xrms}^2(P) + B_{yrms}^2(P) + B_{zrms}^2(P)$$

$$= f_{xrms}^2(P) + f_{yrms}^2(P) + f_{zrms}^2(P) + g_{xrms}^2(P) + g_{yrms}^2(P) + g_{zrms}^2(P)$$

Then the total field is:

$$B_{rms}^2(P) = [U_{hx}^2(P) + U_{hy}^2(P)]\; I_{hrms}^2 + B_{az}^2\cos^2\delta_a$$

$$+ U_{hz}^2(P)\, I^2_{hrms} + \text{cross terms ....}$$

The unit magnetic field can be obtained from MAG-PC by using the configuration set-up in Figs 2, 4, 6, 8 and 9 with 1 Amp of current on the grounding circuit. The total magnetic field at the location of the DAS is known because the DAS monitors it. Therefore, we can compare the theoretical field calculated at this location with the experimental field measured by the DAS.

The quantity referred to as the magnetic field in this formula is actually the magnetic flux density (the magnetic field intensity is denoted by the symbol H and is related to B by the relationship $B = \mu \mu_o H$ where μ_o is the magnetic permeability of a vacuum and μ is the relative magnetic permeability of the medium in question). The magnetic field induction is used instead of the field intensity because the magnetic field measuring devices measure this quantity directly and so it is a matter of convenience.

3.4 The Comparison

A computer program has been written in ASYST (A Scientific System) which reads the unit magnetic field from the MAG-PC output file and the house current and ambient field from the Data Acquisition System (which is ASYST based). The theoretical magnetic field is then calculated using the above formula. A comparison of the rms total magnetic field is given in tables 1-5 for the number of Data Acquisition System frames. The sensitivity of the Data Acquisition System is 0.05 μT. A summary of the results is given below for the five houses followed by some discussion of the results.

1. **23 Brunner Ave.:** Table 1 indicates agreement to better than 0.1 μT for all frames except the second frame.

2. **5 Palace Arch:** Agreement of 0.1 μT is achieved for all frames to one significant figure. The same agreement is obtained to two significant figures for all frames except the fourth frame, see Table 2.

3. **85 Rayne Ave.:** Excellent agreement is achieved between theory and experiment. Table 3 illustrates differences of better than 0.05 μT for all frames.

4. **7 Storey Cres.:** Table 4 shows the correlation between theory and experiment for this location. Differences of 0.2 to 0.5 μT are observed.

5. **69 Gates Cres.:** Agreement of better than 0.05 μT is obtained for all frames, see Table 5.

An uncertainty of 0.1 μT is assigned to the experimental data. This arises from the 0.05 μT sensitivity of the Data Acquisition System and 0.05 μT due to systematic error (ie poor measurements). The theoretical magnetic fields calculated for 7 Storey Crescent do not agree to within this specified uncertainty. However, this may be attributed to inaccurate surveying of the grounding circuit at this location. Variations in the specified location of Data Acquisition System significantly affects the theoretical values as it changes the value of the unit magnetic field calculated by MAG-PC. Therefore, an error in the measurement of house grounding network can cause a variation in the calculated field.

Another important thing to note is that the calculated field is in most cases smaller than the measured field for all the houses studied. This may be due to the implementation of the model.

A listing of the program used for the calculation is given in Appendix A.

Table 1. Comparison of the magnetic fields at 23 Brunner Ave.

Frame #	Bexp (uT)	Bcalc (uT)	Bexp-Bcalc
1	0.37701	0.36830	0.01
2	0.90421	0.68614	0.22
3	0.76413	0.68473	0.08
4	0.64683	0.54451	0.10
5	0.53652	0.52202	0.01
6	0.50546	0.54622	-0.04
7	0.43381	0.41899	0.01
8	0.56135	0.46380	0.10
			----
		rms	0.08

Table 2. Comparison of the magnetic fields at 5 Palace Arch Dr.

Frame #	Bexp (uT)	Bcalc (uT)	Bexp-Bcalc
1	0.28579	0.23403	0.05
2	0.40835	0.32700	0.08
3	0.27163	0.13321	0.14
4	0.12202	0.09769	0.02
5	0.11517	0.12152	-0.01
6	0.12307	0.12609	0.00
7	0.30304	0.25674	0.05
			----
		rms	0.08

Table 3. Comparison of the magnetic fields at 85 Rayne.

Frame #	Bexp (uT)	Bcalc (uT)	Bexp-Bcalc
1	0.24145	0.21765	0.02
2	0.17979	0.16027	0.02
3	0.13073	0.11441	0.02
4	0.17727	0.15474	0.02
5	0.14901	0.12951	0.02
6	0.19845	0.17825	0.02
7	0.16775	0.14871	0.02
8	0.20384	0.18412	0.02
			----
		rms	0.02

Table 4. Comparison of the magnetic fields at 7 Storey Cres.

Frame #	Bexp (uT)	Bcalc (uT)	Bexp-Bcalc
1	1.05570	0.49168	0.56
2	0.58536	0.26762	0.32
3	0.78035	0.42707	0.35
4	0.61664	0.35604	0.26
5	0.58116	0.32927	0.25
6	0.52832	0.29010	0.24
		rms	0.34

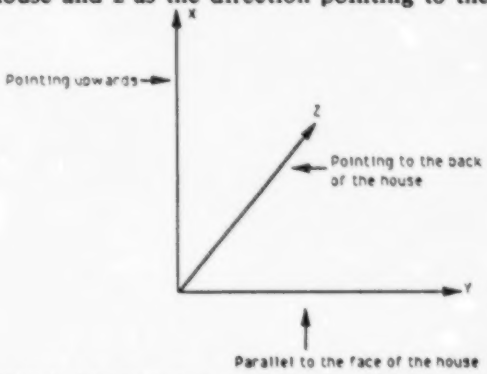
Table 5. Comparison of the magnetic fields at 69 Gates Cres.

Frame #	Bexp (uT)	Bcalc (uT)	Bexp-Bcalc
1	0.06669	0.04898	0.02
2	0.05436	0.03426	0.02
3	0.05292	0.03266	0.02
4	0.05964	0.04058	0.02
		rms	0.02

3.5 The measurement procedure

An outline of the measurement procedure followed in the surveying of the 5 houses is given in this section as a guide to future studies. The measurements outlined in this procedure are required for successful implementation of the model presented in this report. The most important step is the choice of a good coordinate system to enable easy identification of the house grounding network and the distribution network.

The coordinate system used should have x as the direction pointing upwards, y as the direction parallel to the face of the house and z as the direction pointing to the back of the house, ie



A suitable choice of the origin is important so that only a simple translation is required to identify the grounding network and the distribution network on the same plan. Care must also be taken when measuring the actual location of the grounding circuit as sloppy measurements may lead to poor agreement.

The local electrical Hydro utility should be contacted for plans of the distribution network and for linemen to visit the location during the study to measure the current on the network. The Hydro utilities connect their neutral lines everywhere, and consequently small current loops may be present resulting in significant (we have assigned 0.1 μT as significant) ambient fields in a house. If the current loop formed spans a wide area, it is unlikely that a significant field will be present in the house. In this study, only 23 Brunner Ave. had an ambient field of order 0.1 μT. The Hydro linemen should be instructed to measure the net current on the secondary bus and the current on the primary line. If the primary is three phase, then the net current of the three phases must be measured. However, if the insulation on the individual lines is deteriorating, the linemen might refuse to make these measurements. In this case, the epidemiologist/scientist can instruct the linemen to measure the current on the network because the phases of these currents are unknown. A recommendation for future studies is that an instrument be built to clamp around a bunch of wires so that the net current on these wires can be obtained.

A summary of this procedure is:

1. Obtain maps of the electrical power distribution network supplying the house to be tested. These plans should contain information about the voltage step down procedure and the type and number of conductors used. The plans should also contain the same information for neighbouring streets in order to locate possible current loops.

2. On arriving at the house, decide on a particular choice of origin for the coordinate system, keeping in mind that a translation will be required to put the distribution network and the grounding circuit on the same grid. You should also measure out a distance that is easily identifiable on the distribution network plan so as to scale the plan.

3. The first measurement you should make, is to turn off the main power to the house and take a Leeper meter and check for an ambient field. A location far from the Hydro lines is required. It is also useful to check the current on the water-pipe as this is an indication of whether the neighbours' current is using the house grounding network as a return path.

4. At this point we will assume that the linemen from the local electrical utility have arrived. Instruct them to measure the current on the distribution network. Instruct the linemen to clump the secondary bus together and measure the net current. However, they might object to making this particular measurement and if so, have them clip the three individual wires sequentially. If a primary line is present have them measure the current on that also. If a potential current loop exists around the house, then measurements should be made on the sections of the network that constitute the loop.

5. Trace and record the location of the house grounding network. The common practice is to make a ground connection from the service panel to the water-pipe at the point where the pipe enters the house. The conductors in the house can be traced physically, if possible, or with the Hydro 3-axis field sniffer mentioned previously/2/.

6. The Data Acquisition System should be set up to monitor the current on the water-pipe at the point where the grounding connection is made. A suitable choice of location for the auxiliary coil should be made so that it will monitor the ambient field and not be affected by the house grounding network. The 3 axis coil for measuring the total field must be oriented to correspond to the coordinate system. This coil is labeled A, B , C corresponding to X, Y, Z.

4. Recommendations

The method of implementing the model needs to be reviewed to try and account for the low theoretical fields. Improvement in the model may be achieved by examining the individual components of the field, ie B_x, B_y and B_z, to see how the model predicts these components. Initial investigations on the 23 Brunner data have revealed poor agreement between the theoretical and experimental values of the individual components, even though the agreement of the total field is quite good. Table 6 illustrates this fact.

An instrument needs to be developed to enable the net current on a group of parallel wires to be measured. This will aide in the study of the ambient magnetic field present in a particular house due to the distribution network as the net current on the distribution network can be measured.

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2. R. Scheer, A 3-Axis Probe for 60-Hz Magnetic Fields. Research Report No 89-163-K.

3. K.E. Donnelly, A Data Acquisition System for Residential Magnetic Field Source Characterization. Research Report (to be submitted).

4. E.G. Prestin, Amer. Public Power Association Engineering and Operations Workshop, Washington, D.C, March 15 (1989).
   R. Graves, Toronto Hydro, (Priv. Comm.).

Table 6. Comparison of the experimental and theoretical individual magnetic field components (Bx, By and Bz) for 23 Brunner Ave.

Frame #	$B_x$exp (uT)	$B_x$calc (uT)	$B_x$exp-$B_x$calc
1	0.66272	0.83115	-0.17
2	0.98657	1.17020	-0.18
3	0.25733	0.36499	-0.11
4	0.33482	0.48554	-0.15
5	0.41025	0.42953	-0.19
6	0.22198	0.33632	-0.12
7	0.60007	0.78902	-0.19
8	0.58109	0.77670	-0.20
			----
		rms	0.17

Frame #	$B_y$exp (uT)	$B_y$calc (uT)	$B_y$exp-$B_y$calc
1	0.17381	0.10672	0.07
2	0.20646	0.15026	0.06
3	0.11610	0.04687	0.06
4	0.10121	0.06234	0.04
5	0.05123	0.05515	-0.00
6	0.11479	0.04318	0.07
7	0.15865	0.10131	0.06
8	0.14516	0.09972	-0.06
			----
		rms	0.06

Frame #	$B_z$exp (uT)	$B_z$calc (uT)	$B_z$exp-$B_z$calc
1	0.07102	0.09303	-0.02
2	0.19761	0.28306	-0.09
3	0.19963	0.14107	0.06
4	0.19255	0.21456	-0.02
5	0.35763	0.15784	0.20
6	0.22821	0.06442	0.16
7	0.23163	0.07095	0.16
8	0.14935	0.12878	0.02
			----
		rms	0.11

Appendix A : ASYST program used to implement formula of section 3.3

```
\ This section of program reads in the field data generated by MAGPC which
\ deals with the fields grounding network.

\ DEFINITION SECTION

   REAL DIM[ 50 , 4 ] ARRAY MAGPC.FIELD
                  \ Field in the house due house grounding network (MAGPC)
   REAL DIM[ 50 , 4 ] ARRAY MAGPC.CO-ORDINATES
                  \ Co-ordinates over which the MAGPC fields
                  \ were calculated

   10 STRING FILENAME           \ Name of MAGPC file containing data
   50 STRING MAGPC.TITLE        \ Title of MAGPC file - usually test location
   80 STRING MAGPC.COMMENT      \ Comment in MAGPC file
   REAL SCALAR MAGPC.START       \ Co-ordinate start position of MAGPC calc.
   INTEGER SCALAR MAGPC.#.STEPS \ Number of steps involved in calculation
   REAL SCALAR MAGPC.INCREMENT  \ Increment of co-ordinates in MAGPC calc.

: GET.NAME&OPEN       \ Prompts for the name of the data file and opens it

   CR ." THE NAME OF THE MAGPC FILE PLEASE? "
   "INPUT DEFER> BASIC.OPEN  \  OPEN THE REQUESTED FILE
;


: READ.MAGPC.FILE             \ Reads the MAGPC data files

   SCREEN.CLEAR
   CR ." READING MAGPC FILE "
   "BASIC.READ MAGPC.TITLE ":=
   4 1 DO "BASIC.READ LOOP
   BASIC.READ DROP MAGPC.START := MAGPC.#.STEPS := MAGPC.INCREMENT :=
   "BASIC.READ MAGPC.COMMENT ":=
   3 1 DO "BASIC.READ LOOP
   11 4 SCI.FORMAT

   MAGPC.#.STEPS 1 + 1 DO
          BASIC.READ DROP
          5 1 DO
                MAGPC.FIELD [ J , I ] :=
               LOOP
          5 1 DO
                MAGPC.CO-ORDINATES [ J , I ] :=
              LOOP
          LOOP

   BASIC.CLOSE                          \ Close the data file
  ;
```

```
: DO.READ
                    \ Typing this word will invoke the above routines and
                    \ store the data on the house fields

    GET.NAME&OPEN
    READ.MAGPC.FILE
;
```

This section calculates the theoretical value of the magnetic field according to the formula presented in section 3.3.

```
  \ Definitions Section

      REAL DIM[ 3 ] ARRAY AMB.FIELD
                    \ Ambient mag. field obtained using the MAGPC
      REAL DIM[ 4 ] ARRAY UNITMAG.FIELD
                    \ A Unit of mag. field due to grounding circuit
                    \ obtained from MAGPC
      REAL DIM[ 3 ] ARRAY FARR
      REAL DIM[ 3 ] ARRAY GARR
                    \ Constants used in the theoretical calculation of the
                    \ magnetic field
      REAL DIM[ 8 , 3 ] ARRAY B.COMPONENTS
                    \ The theoretical components of the magnetic field
      REAL DIM[ 8 ] ARRAY BTOTAL
                    \ The theoretical total of the magnetic field
      REAL DIM[ 128 , 2 , 8 , 8 ] ARRAY CAPTURED.EVENTS.SEQUENCE
                    \ Array that contains the information acquired by
                    \ the Data Acquisition System (DAS)
                    \ Index 1 : the number of samples
                    \ Index 2 : 1 - magnitude
                    \           2 - phase
                    \ Index 3 : harmonic number
                    \           i.e. zeroth harmonic is 1
                    \ Index 4 : As described previously
      REAL DIM[ 8 , ] ARRAY TOTMAG.FLD
                    \ Mean of total mag. field  obtained using the DAS
      REAL SCALAR HOUSE.CURRENT
                    \ The mean of the house current obtained using the DAS
      REAL SCALAR HOUSE.PHASE
                    \ The mean of the phase of the above house current
      REAL SCALAR AMB.FIELD
                    \ The mean of the ambient field obtained using the DAS
      REAL SCALAR AMB.PHASE
                    \ The mean of the phase of the above ambient field
      REAL SCALAR DOSIMETER.LOCATION
                    \ The co-ordinates of the DAS
      REAL SCALAR ARRAY.LOCATION
                    \ The array index which contains the DAS location
      INTEGER SCALAR IND
                    \ Index used to keep track of the frame
      INTEGER SCALAR FRAME.NO
                    \ Number to indicate which frame to read of the data file
```

```
: OBTAIN.AMB.FIELD
                    \ Routine to retrieve the values of magnitude and phase of
                    \ the ambient field obtained by the DAS
      CAPTURED.EVENTS.SEQUENCE DUP
      XSECT[ ! , 1 , 1 , 8 ] [ 100 ] AMB.FIELD :=
      XSECT[ ! , 2 , 1 , 8 ] [ 100 ] AMB.PHASE :=
;

: OBTAIN.HOUSE.CURRENT
                    \ Routine to retrieve the values of the magnitude and phas
                    \ of the house current obtained using the DAS
        CAPTURED.EVENTS.SEQUENCE DUP
        XSECT[ ! , 1 , 1 , 4 ] [ 100 ] HOUSE.CURRENT :=
        XSECT[ ! , 2 , 1 , 4 ] [ 100 ] HOUSE.PHASE :=
;

: OBTAIN.UNIT.MAG.FIELD
                    \ Routine to retrieve the unit magnetic field at the
                    \ dosimeter location
      MAGPC.FIELD XSECT[ ARRAY.LOCATION , ! ] 1E6 *
      REV[ 1 ] UNITMAG.FIELD :=
;

  : BMAG.CALC
                    \ Routine to calculate the theoretical magnetic field,
                    \ total and individual components, based on the model
                    \ outlined in this report ...  It invokes the routines
                    \ defined above

                    \ Initialization Section

      0. DOSIMETER.LOCATION :=
      0. AMB.FIELD  :=
      0. FARR  :=
      0. GARR  :=
      0. ARRAY.LOCATION :=
      0. DUP MEAN.HOUSE.PHASE := HOUSE.CURRENT :=
      0. DUP MEAN.AMB.PHASE := AMB.FIELD :=
      0. UNITMAG.FIELD :=
      0. B.COMPONENTS XSECT[ IND , ! ] :=
      0. BTOTAL [ IND ] :=

      OBTAIN.AMB.FIELD

      OBTAIN.HOUSE.CURRENT

      OBTAIN.UNIT.MAG.FIELD

     MAGPC.DIST.FIELD XSECT[ ARRAY.LOCATION , ! ] REV[ 1 ] 1E6 *
     [ 3 ] ABS MEAN.AMB.FIELD
     AMB.FIELD [ 3 ] := STACK.CLEAR
```

```
    \ The following lines of code are the actual field calculation portion

    AMB.FIELD AMB.PHASE COS * UNITMAG.FIELD
    HOUSE.CURRENT * HOUSE.PHASE COS * SUB[ 1 , 3 ] + FARR :=

    AMB.FIELD AMB.PHASE SIN * UNITMAG.FIELD
    HOUSE.CURRENT * HOUSE.PHASE  SIN * SUB[ 1 , 3 ] + GARR :=

    FARR DUP * GARR DUP * + SQRT B.COMPONENTS XSECT[ IND , ! ] :=
    B.COMPONENTS XSECT[ IND , ! ] DUP * ^SUM [ 3 ] SQRT
    BTOTAL  XSECT[ IND , ! ] :=
;
```

This section reads in the experimental total field from the Data Acquisition System as well as the magnitude and phase of the current on this network. Th magnitude and phase of the ambient field is also read in here.

```
        \ Definition Section

         REAL DIM[ 8 , 128 ] ARRAY TOTAL.MAG.FIELD
                      \ Array to store the total magnetic field measured
                      \ using the DAS for a max of 8 frames.
         REAL DIM[ 8 ] ARRAY FIELD.DIF
                      \ Array to store the difference between the experiment
                      \ and theoretical values of the total magnetic field.
         INTEGER DIM[ 10 ] ARRAY DATE.STAMP
                      \ Array to store the date stamp (not significant)
         INTEGER DIM[ 10 ] ARRAY TIME.STAMP
                      \ Array to store the time stamp (not significant)
         10 STRING INDENTIFIER      \
         10 STRING LOCATION         \  Co-ords. of the DAS in the house
         10 STRING FILE.DATE        \
         10 STRING SEQUENCE.NO      \
         10 STRING REMARKS.1        \
         10 STRING REMARKS.2        \
         10 STRING NAME.FOR.FILE    \  Name of file containing the DAS data
         15 STRING DATEBACK         \
         15 STRING TIMEBACK         \

         REAL DIM[ 1 ] ARRAY INTERVAL  \
         REAL DIM[ 1 ] ARRAY DURATION  \

         INTEGER SCALAR NO.ARRAYS.STORED
         INTEGER SCALAR CORIND
         REAL SCALAR INDX
         REAL SCALAR INDY
         REAL SCALAR INDZ

         FILE.TEMPLATE                  \ File template : defines the
             6 COMMENTS                 \ the layout of the file.
             REAL DIM[ 1 ] SUBFILE
             2 TIMES
         END
```

```
: READ.AST.FILE              \ Reads the data file of data obtained
                             \ using the DAS

        (DEF) SCREEN.CLEAR
        ." NAME OF DAS FILE TO BE READ ? "
        "INPUT "DUP
        NAME.FOR.FILE ":=
        DEFER> FILE.OPEN

        \ READ COMMENTS

            1 COMMENT> INDENTIFIER ":=
            2 COMMENT> LOCATION ":=
            3 COMMENT> FILE.DATE ":=
            4 COMMENT> SEQUENCE.NO ":=
            5 COMMENT> REMARKS.1 ":=
            6 COMMENT> REMARKS.2 ":=

       \ READ DATA LOGGING PARAMETERS

            1 SUBFILE INTERVAL FILE>ARRAY
            2 SUBFILE DURATION FILE>ARRAY

        \ ASCERTAIN # OF DATA ARRAYS STORED

            FILE.CONTENTS
            SWAP DROP
            2 - DUP
            3 MODULO -
            3 /
            NO.ARRAYS.STORED :=

;
: READ.ARRAY  \ Routine to read the DAS arrays for each frame

            SCREEN.CLEAR  CR ." READING FILE : FRAME.NO.  " I .
            FRAME.NO SUBFILE DATE.STAMP FILE>ARRAY
            DATEBACK DATE.STAMP ARRAY>"
            FRAME.NO 1 + SUBFILE TIME.STAMP FILE>ARRAY
            TIMEBACK TIME.STAMP ARRAY>"
            FRAME.NO 2 + SUBFILE CAPTURED.EVENTS.SEQUENCE
            FILE>ARRAY
                  \ Reads array containing information on the
                  \ measured current and fields with phase angle
            CAPTURED.EVENTS.SEQUENCE DUP DUP
            XSECT[ ! , 1 , 1 , 5 ] DUP * SWAP
                \ 5 is the x-magnetic field
            XSECT[ ! , 1 , 1 , 6 ] DUP * + SWAP
                \ 6 is the y-magnetic field
            XSECT[ ! , 1 , 1 , 7 ] DUP * + SQRT
                \ 7 is the z-magnetic field
            TOTAL.MAG.FIELD XSECT[ IND , ! ] :=
                \ Total magnetic field is calculated as the sqrt
                \ of the sum of the squares of the components
```

```
        \ the next few lines calculate the mean of the individual
        \ frames of the magnetic field components

        FILE.CLOSE              \ Closes the DAS data file
;

: DO.COMPARISON         \ Invokes the above routine as well as the
                        \ routine to calculate theoretical values
                        \ of the fields.

            SCREEN.CLEAR
            CR ." WHICH IS THE VARIABLE CO-ORDINATE IN THE MAGPC FILE? "
            CR ." 1. X CO-ORDINATE "
            CR ." 2. Y CO-ORDINATE "
            CR ." 3. Z CO-ORDINATE "
            CR ." ENTER (1-3) => "
            #INPUT CORIND :=
            CR ." "
            CR ." "
            CR ." ENTER THE POSITION OF THE DATA ACQUISITION SYSTEM "
            CR ." ENTER X => " #INPUT INDX :=
            CR ." ENTER Y => " #INPUT INDY :=
            CR ." ENTER Z => " #INPUT INDZ :=
            MAGPC.CO-ORDINATES
            CASE CORIND
                1 OF [ 1 , 3 ] INDX - ENDOF
                2 OF [ 1 , 2 ] INDY - ENDOF
                3 OF [ 1 , 1 ] INDZ - ENDOF
            ENDCASE
            MAGPC.INCREMENT / ABS 1 + ARRAY.LOCATION :=

            READ.AST.FILE
            NO.ARRAYS.STORED 1 + 1 DO
                    I IND := I 3 * FRAME.NO :=
                    READ.ARRAY BMAG.CALC
                LOOP FILE.CLOSE
;


: DO.WORD                   \ A routine to generate an array of the mean
                        \ total fields for easy comparison to
                        \ theoretical results
    9 1 DO
            TOTAL.MAG.FIELD XSECT[ I , ! ] [ 100 ]
                                        TOTMAG.FLD [ I ] :=
           TOTMAG.FLD [ I ] BTOTAL [ I ] - FIELD.DIF [ I ] :=
        LOOP ;
```

```
: DO.PRINT    \ Routine to print the theoretical and experimental val
              \ of the total magnetic field as well as the difference
             \ between the two.

        SCREEN.CLEAR
        CR ." A COMPARISON OF THE EXPERIMENTAL AND THEORETICAL "
        CR ."      TOTAL MAGNETIC FIELDS "
        CR ." "
        CR ." "
        CR ."     Bexp          Bcalc       Bexp-Bcalc
        CR ." "
        NO.ARRAYS.STORED 1 + 1 DO
        FIELD.DIF [ I ] BTOTAL XSECT[ I , ! ] MEAN TOTMAG.FLD
        XSECT[ I , ! ] MEAN
        CR  .  ."     " . ."     " .
       LOOP ;
 : DO.ALL              \ Invokes the previously defined routines
                       \ DO.READ and DO.COMPARISON.
          SCREEN.CLEAR
          DO.READ
          DO.COMPARISON
 ;

\ To run the program type DO.ALL
```

A User's guide for the ASYST program :

This program works in the ASYST language system. Load ASYST onto your computer, place the floppy disk labelled SOURCX into the A drive and type :

ECHO.OFF LOAD A:READ.MAG LOAD BMAG.AST LOAD READ.FILE <CR>

Once the loading has finished place the floppy disk with the relevant data into the A drive. This disk should contain the unit magnetic field obtained from MAGPC (extentsion .DAT) for the specific location and the file generated by the Data Acquisition System while monitoring this location. Now type :

DO.ALL

The program will prompt you for the name of the MAGPC file which contains the unit magnetic field for the grouding circuit of the house. The program will also prompt for the co-ordinate which is varying in the MAGPC file (i.e. in the MAPGC file one of x,y and z will be incremented throughout the data file while the other two co-ordinates remain constant). The user will also be prompted for the co-ordinates of the Data Acquistion System in the co-ordinate system used to generate the MAPGC data file (see section 3.2). The program then requires the name of the file generated by the Data Acquisition System. Once the program has finished executing, it will have produced a table of results containing the measured and theoretical total magnetic fields and the difference of the two.